OST TECHNICAL PROGRESS REPORT
FY 2001 RESULTS

TITLE: Steady-Flow, Low-NOx Combustion Team Annual Report

TEAM MEMBERS:
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DESCRIPTION:

The Low-NOx Combustion Team is a part of the Gas Energy Systems Dynamics Focus Area at NETL. The primary focus of the team is very low emissions combustion, particularly for advanced gas turbine engines. The range of activities includes modeling and simulation and detailed laboratory-scale studies, as well as larger, bench-scale investigations with sub-scale commercial hardware. Primary funding for the team has historically come from the Advanced Turbines Systems (now High Efficiency Engines and Turbines) Product Team. Additional support has also been received from the Power Systems/Advanced Research Product Team for single particle studies.

RESEARCH OBJECTIVES:

The following research objectives were established at the beginning of FY 2001:

<u>Trapped Vortex Combustor (TVC)</u>: Conduct detailed CFD simulations to guide the design of an NETL rich-burn, quick-quench, lean-burn (RQL)/TVC prototype. Complete preliminary testing of the RQL/TVC prototype at NETL using natural gas fuel.

<u>Simulation-Validation Studies</u>: Fabricate two nozzle sets for the Sim-Val combustor (one for testing at Sandia National Lab), modify the low emissions combustor test and research (LECTR) facility to accommodate burner and optical access requirements, add hydrogen flow loop for fuel doping, perform initial nozzle characterization tests at one atmosphere pressure at Sandia, and begin initial parametric testing of nozzle at NETL.

<u>Lab-Scale Porous Media Burner (PMB):</u> Complete current PMB experimental studies, complete the analysis of the resultant data, and prepare reports and manuscripts for publication.

<u>Single Particle Characterization:</u> Develop improved shape/drag relationships, perform char characterization studies to help validate combustion sub-models, and begin characterization studies of biomass fuels.

In addition, soon after the beginning of the fiscal year, two relatively high priority projects were added to the mix of team activities for the year. These included a support effort to develop a reheat combustor for the Clean Energy Systems Program and a carryover from FY00 of two tasks in support of the Humid Air Turbine Program.

LONG TERM GOALS / RELATIONSHIP TO NETL'S PRODUCT LINES:

The demand for efficient, clean, and cost-effective power generation poses the challenge of increasing combustion temperatures and pressures while lowering NO_x and CO emissions. In addition, the development of new cycle concepts or the application of these systems to unusual fuels such as biomass fuel gas, landfill gas, etc., puts additional demands on the combustion system to continue to meet the required emissions limits. To address some of these issues, this team operates a LECTR facility. The LECTR is a versatile test facility with capabilities for evaluating a variety of low emissions combustion concepts at temperatures and pressures representative of gas turbine applications. The primary objective of this activity is to provide test facilities and engineering support to NETL customers through programs such as the ATS University-Industry Consortium and through CRADA participation with industrial partners.

This team is also interested in advanced research such as that supported by the Power Systems/Advanced Research Product Team. An example in our current suite of activities is the characterization of particle shape and drag. This work is being performed in the single particle electrodynamic balance apparatus at NETL.

SUMMARY ACCOMPLISHMENTS:

<u>Trapped Vortex Combustor</u>:

- Continued collaborations with Air Force Research Laboratory (AFRL) and other industrial partners interested in TVC technology.
- Completed detailed CFD simulations of TVC to evaluate and optimize design options.
- Completed design, fabrication, and facility modifications for NETL RQL/TVC prototype testing.
- Completed preliminary testing of NETL RQL/TVC prototype. These results are described in more detail below.
- Results of this activity were published at the 2000 American Flame Research Committee International Symposium and at the 2001 Advanced Gas Turbines Systems Research Combustion Workshop.

<u>Simulation-Validation Studies (SimVal):</u>

- Completed initial design of the SimVal project rig.
- Initiated collaboration with Sandia National Laboratory-Combustion Research Facility (SNL-CRF).
- Initiated collaboration with CFD Research, Inc. on large eddy simulation (LES) code validation.
- Developed a dynamic model of acoustic response of the combustor to an acoustic velocity source.
- As a result of the SNL-CRF collaboration, collaboration with the International Energy Agency (IEA) Combustion Annex has been initiated.

<u>Lab-Scale Porous Media Burner (PMB):</u>

- Completed central composite, statistically-designed laboratory experiment, evaluating the combustion behavior of truncated-cone PMBs of two different materials (sintered tungsten and a mullite-bonded alumina) fired with two different fuels.

- Completed a paper titled, "Spatial Variation of Combustion Product Composition In a Conical Porous Medium Burner," by J. S. Ontko, K. H. Casleton, and J. L. Spenik, for presentation at the Fall Meeting of the Western States Section of the Combustion Institute, October 15-16, 2001.

Single Particle Characterization:

- Completed full characterization of several sets of particles, including polystyrene calibration spheres, quartz, and coal. These characterizations included measurements of particle drag-to-mass ratios, as well as volume and area assessments, for each particle.
- Initiated similar characterization of char samples obtained from Sandia National Lab-Combustion Research Facility (SNL-CRF).

Clean Energy Systems Support

- Completed numerous zero- and one-dimensional model studies of reheat combustor residence times necessary for acceptable CO burnout. These simulations were performed for both steam and CO_2 diluents.
- Prepared and presented a paper titled "A Comparison of Gas Turbine Concepts Suitable for Integration with CO_2 Sequestration" that discussed these modeling results at the 2001 Joint International Combustion Symposium.

Humid Air Turbine (HAT)

- Completed testing of a catalytic pilot and a liquid-fueled nozzle for HAT applications.
- Prepared a manuscript titled "Humid Air NOx Reduction Effect on Liquid Fuel Combustion" for presentation at the 2002 ASME Turbo Expo.

RESULTS:

Highlights of selected research activities are described below:

Trapped Vortex Combustor:

The Trapped Vortex Combustor (TVC) concept is a revolutionary combustor design that may have the potential to exceed the fuel-flexibility and emissions standards of conventional gas turbine combustors. The TVC concept has been conceived and investigated at the Air Force Research Laboratory (AFRL) for several years by Roquemore and colleagues. Recently, the Strategic Environmental Research and Development Program (SERDP) selected the TVC Project as the "Project of the Year" for 2001.

The recent focus of the Next Generation Turbine Program toward improving fuel-flexibility, cost, and reliability of gas turbine systems has spawned the idea of using the TVC approach for stationary power applications. The NETL/AFRL collaboration has focused on the development of a rich-burn, quick-quench, lean-burn (RQL) combustor using the TVC concept. One goal of this effort is to assess the performance of this technology for fuels with fuel-bound nitrogen such as might be found for fuel gas from coal, biomass, or other unconventional fuels.

In a trapped vortex combustor, a cavity in the combustor wall is used to provide flame stability. The flow in the cavity is nearly independent of the main stream so that potential upsets in the main-air flow do not upset the flame stabilization characteristics. In the RQL/TVC approach, all of the fuel is injected into the cavity. Air is also injected into the cavity, but at a rich equivalence ratio so that it is insufficient to complete the combustion of the fuel. The main air is introduced along the centerline of the combustor to complete the combustion of the products from the fuel-rich cavity. Figure 1 shows a schematic representation of the RQL/TVC concept, as well as a photograph of the initial hardware developed for this concept. Extensive computational fluid dynamics analyses have been performed to optimize the main air distribution.

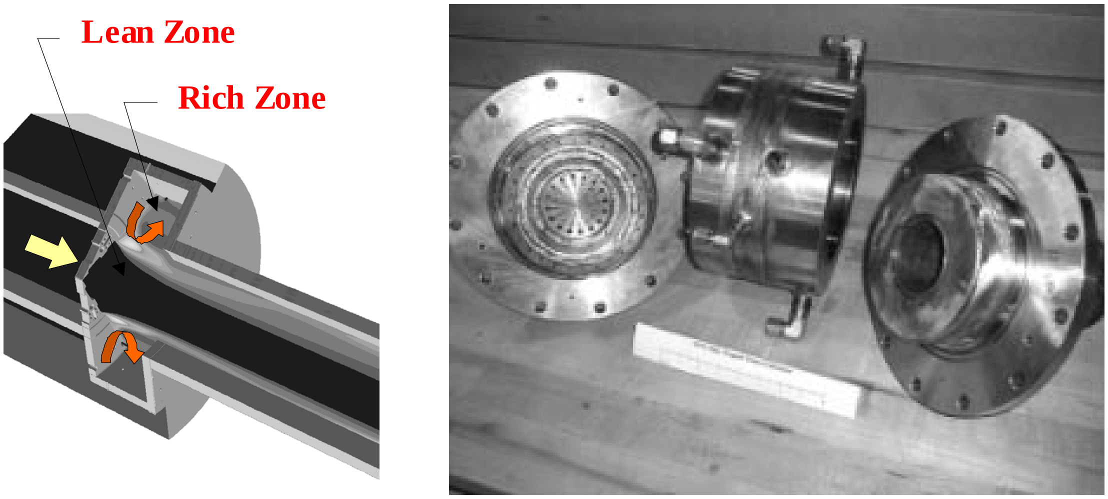

Figure 1. NETL Trapped Vortex Combustor for RQL applications. Drawing on the left shows the lean and rich zones in the assembled combustor. Picture on the right shows the actual hardware.

Preliminary tests were performed using natural gas as the fuel. For all of the tests to date, the inlet air temperature was set at 644K (700F). Tests were conducted over a wide range of operating conditions, and several different variables were investigated. In spite of the fact that this was the first RQL/TVC combustor ever designed, the preliminary results were very encouraging. As part of this test program, the effect of steam addition into the main air stream was investigated. Figure 2 shows the NOx and CO emissions observed with and without steam addition. These data were taken at a combustor pressure of 10 atmospheres. Without steam injection, the CO levels were very low over much of the operating range, and very lean operating conditions could be achieved with no fuel-staging strategy. The NO_x levels were 40-60 ppm without steam injection, but actually decreased below 20 ppm when steam was injected into the main air stream at a 25 wt.% loading.

The results from this work have been presented at the 2000 American Flame Research Committee International Symposium [3] and at the 2001 Advanced Gas Turbine Systems Research – Combustion Workshop [4].

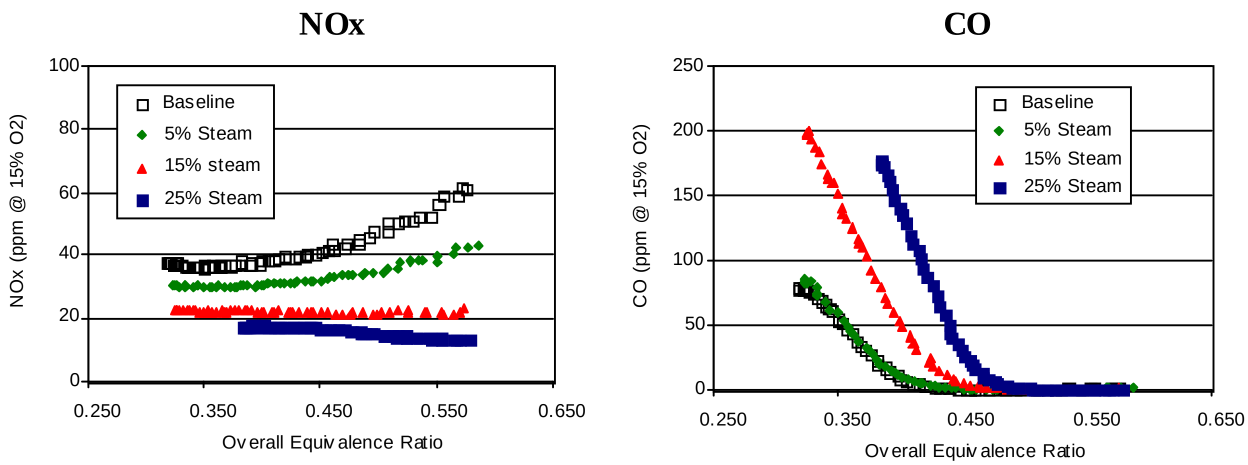

Figure 2: Preliminary results from RQL/TVC tests on natural gas
[p = 10 atm, T_{in} = 700F, ϕ_{rich} = 1.5, τ_{rich} = 30 ms (cold)].

The NETL/AFRL collaboration continues to benefit both organizations. In addition, NETL is seeking to develop additional external collaborations. At least 3 different industrial partners were presented with information from this TVC project. Two or more of these organizations will be testing TVC approaches for their proprietary applications.

References:

1. Straub et al. (2000). Simulations of a rich quench lean (RQL) trapped vortex combustor. American Flame Research Committee (AFRC) International Symposium, Newport Beach, CA, September 2000.
2. Richards, G. A., and Straub, D. L. (2001). Combustion research at NETL. Advanced Gas Turbine Systems Research (AGTSR) Combustion Workshop, Charleston, SC, July 2001.

Simulation-Validation Studies (SimVal)

SimVal is a research project specifically designed to produce benchmark-quality data on physical processes that are needed to model low-emission turbine combustion flames for both current and future generations of stationary power systems. The need for these data has been highlighted at U.S. Department of Energy workshops [1,2]. Data produced from the SimVal project are expected to contribute to ongoing NETL projects in simulation development [3], as well as technology development programs, including DOE's Vision 21 program [4], the Integrated Gasification Combined Cycle (IGCC) Programs, Renewables Programs, and the Hydrogen Program.

The SimVal combustor will operate at flow rates, pressures, air preheat temperatures, and flow velocities representative of future gas turbine power systems. In addition, the SimVal facility will have full optical access for detailed flow field and species measurement. A significant feature will be the addition of hydrogen doping to the baseline natural gas fuel. Because hydrogen will dramatically accelerate the chemical processes in combustion, the addition of controlled quantities of hydrogen to the baseline fuel will provide data useful to assess numeric predictions of the effect of fuel type. This approach is particularly important to fuels that contain a mixture of hydrocarbons and hydrogen, rather than pure hydrogen alone. These data would therefore address those applications which may include combining H_2/CO mixtures generated in small-scale biomass gasifiers, but burned with a

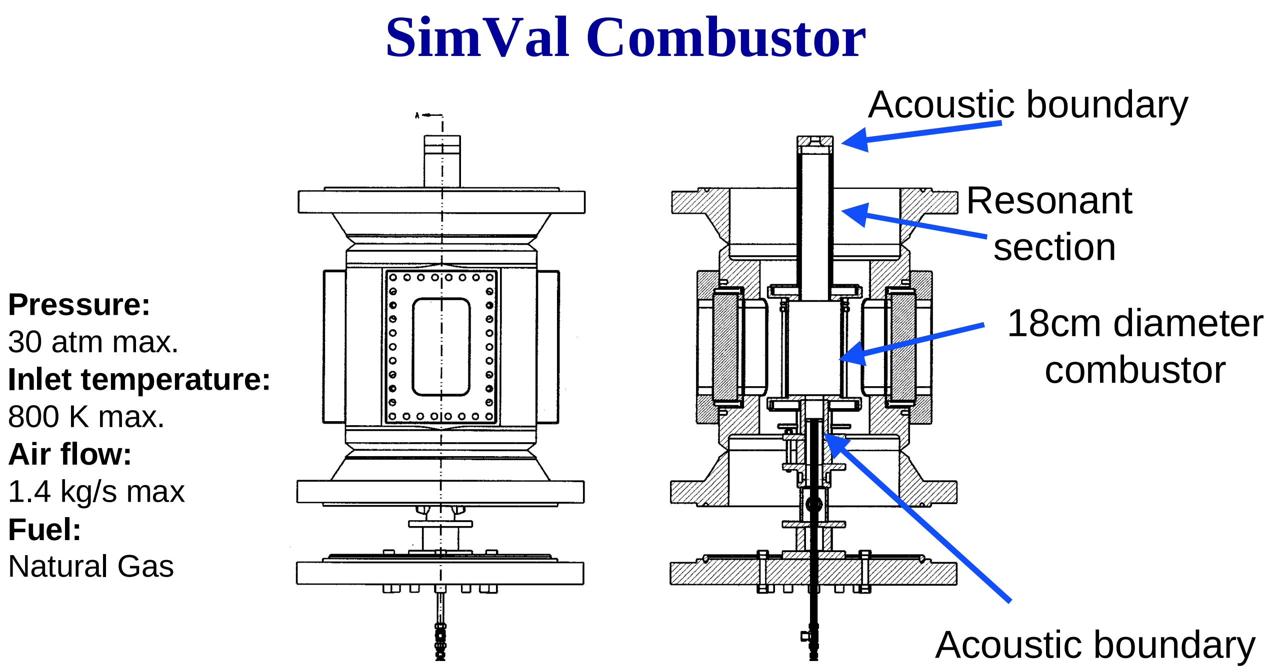

Figure 3. The NETL SimVal Combustor

larger quantity of natural gas.

A second feature of the SimVal combustor is the incorporation of flow, thermal, and acoustic boundary conditions that are relevant to real engine configurations, yet retain easily quantified acoustic response. Knowledge of the acoustic response is important because it is necessary to adequately describe the combustion dynamics of the system. Experimental data on combustion dynamics is typically not collected in a manner that can allow quantitative comparisons to model predictions, often because the acoustic boundaries are unspecified. To resolve these uncertainties, features of the SimVal combustor have been specifically designed to remove uncertainty over boundary conditions, so that model development can focus on dynamic changes resulting from fuel issues such as the hydrogen addition described above.

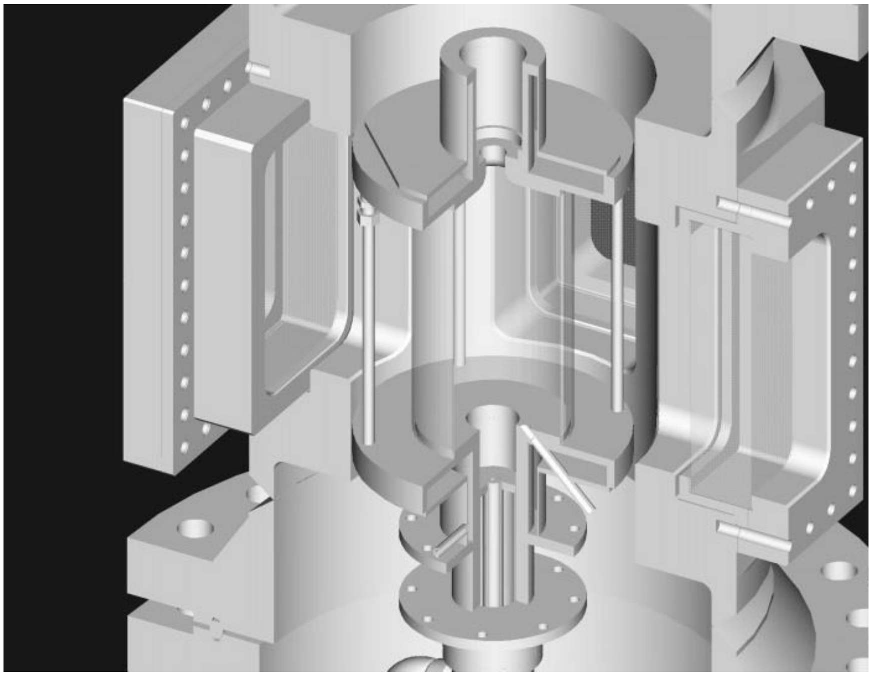

Figure 4. Close-up view of optically-accessible combustion region.

A sketch of the SimVal combustor, as currently being built, is shown in Figures 3 & 4. Optical access is available through the entire combustion region. The combustor major diameter is 18 cm, which is representative of the dome height of annular combustors, and the tube diameter of can-style combustors. A close up of the combustor region (Figure 4) shows the quartz-tube that comprises the body of the combustion chamber. Optical access is available through up to four optical ports surrounding the combustion section. A resonant section added to the exhaust establishes the acoustics of the combustor. For the geometry shown, the first resonant mode is 500Hz – a frequency range of interest to fielded gas turbine engines. The second resonant mode, near 1400Hz, may also be excited, but frequencies in the kHz range are less commonly encountered for a combustor geometry typical of stationary power turbines. In either case, the resonant section of the combustor can be modified to produce other frequency ranges of interest without appreciably modifying the flow field in the combustor.

To maximize the unique potential for data acquisition in the SimVal experiment, NETL plans to partner with the Department of Energy's Sandia National Laboratory – Combustion Research Facility. Sandia will apply the most advanced diagnostics possible to this full-scale combustor, recording data that would otherwise be inaccessible. Again, these data will help resolve questions about the choice of combustion submodels appropriate for clean turbine power generation.

In addition, NETL will leverage both current and proposed research projects among US and overseas research groups. By developing an internet-based capability for the tests, NETL expects to invite web-based participation in tests, essentially forming a co-laboratory with other researchers. This approach will maximize the benefit of these large-scale tests by making the experimental planning, operation, and resulting data immediately available to the community that will use it.

References:

1. Next Generation Systems: Combustion Barriers and R&D Opportunities, AGTSR Combustion Workshop VI, Blacksburg VA, April 19, 1999. http://cufp.clemson.edu/scies/
2. AGTSR Combustion Workshop VII, Charleston, SC, July 31-Aug 2, 2001. Sponsored by the South Carolina Institute for Energy Studies. http://cufp.clemson.edu/scies/
3. LES Software for Design of Low Emission Combustion Systems for Vision 21 Plants, DOE Contract DE-FC26-00NT40975 (Duration: 9/29/00 - 9/30/03).
4. Vision 21 Technology Roadmap, http://www.netl.doe.gov/coalpower/vision21/v21rdmp.pdf

TEAM PUBLICATIONS:

1. Ogunsola, O., Shadle, L. D., Casleton, K. H., and Mei, J. (2001). Investigation of the causes of seasonal variation of NOx emission from waste coal-fired circulating fluidized bed utility plants. Ind. & Engr. Chem. Res., 40, p. 3869.

2. Ogunsola, O. I., Shadle, L. J., Casleton, K. H., and Mei, J. S. (2001). Effect of season on NOx emission from commercial waste coal-fired circulating fluidized bed boilers. Proceedings of the 16th International Conference on Fluidized Bed Combustion, ed. D.W. Geiling, FBC01-090, Reno, NV, May 13-16, 2001.

3. Lewis, R. E., Casleton, K. H., Richards, G. A., Straub, D. L., and Rogers, W. A. (2001). A comparison of turbine combustion concepts suitable for integration with CO_2 sequestration. American Flame Research Committee (AFRC) 2001 Joint International Combustion Symposium, Kauai, HI, September 2001.

4. Ontko, J. S., Casleton, K. H., and Spenik, J. L. (2001). Spatial variation of combustion product composition in a conical porous medium burner. Presented at the 2001Fall Meeting of the Western States Section/Combustion Institute, October 15-16, 2001, Salt Lake City, UT.

5. Chen, A. G., Maloney, D. J., and Day, W. H. (2002). Humid air NOx reduction effect on liquid fuel combustion. ASME Turbo Expo 2002, June 3-6, 2002, Amsterdam, The Netherlands, (Submitted for presentation/publication).

ACKNOWLEDGMENTS:

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